Express Mail Label No. EV349694615US Dated: 9/25/03

Docket No.: 06670/000M972-US0
(PATENT)

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Patent Application of:
Michel Morin

Application No.: 10/601,065

Confirmation No.: 5521

Filed: June 20, 2003

Art Unit: N/A

For: FIBER BRAGG GRATING INTERFEROMETERS FOR CHROMATIC DISPERSION COMPENSATION

Examiner: Not Yet Assigned

CLAIM FOR PRIORITY AND SUBMISSION OF DOCUMENTS

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Dear Sir:

Applicant hereby claims priority under 35 U.S.C. 119 based on the following prior foreign application filed in the following foreign country on the date indicated:

Country	Application No.	Date
Canada	2,391,179	June 21, 2002

In support of this claim, a certified copy of the said original foreign application is filed herewith.

Dated: September 25, 2003

Respectfully submitted,

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Specification and Drawings, as originally filed, with Application for Patent Serial No: **2,391,179**, on June 21, 2002, by **TERAXION INC.**, assignee of Michel Morin, for "Fiber Bragg Grating Interferometers for Chromatic Dispersion Compensation".

Agent certificateur/Certifying Officer

September 8, 2003

Date

FIBER BRAGG GRATING INTERFEROMETERS FOR CHROMATIC DISPERSION COMPENSATION

FIELD OF THE INVENTION

The present invention relates to optical communication systems and more particularly concerns the compensation of chromatic dispersion in such systems.

BACKGROUND OF THE INVENTION

The present invention addresses the compensation of chromatic dispersion in optical communication systems. Chromatic dispersion designates the spectral dependence of the group velocity of light propagating along an optical fiber link[1,2]. It produces a distortion and lengthening of light pulses propagating along an optical fiber, which can eventually result in the overlap of neighbouring pulses. This limits the distance over which an optical signal can be transmitted and maintained in a detectable form without reshaping. It is especially troublesome in high bit rate systems, since the distortion of the optical signal resulting from chromatic dispersion scales as the square of the signal bandwidth. Chromatic dispersion is a major limiting factor in 10 and 40 Gb/s systems.

Various chromatic dispersion compensation techniques have been devised and are reviewed in Chapter 9 of [2]. Dispersion compensation is still a field of active research, aimed at improving performances and tunability and reducing costs[3-16]. A notable advance has been the achievement of multi-channel dispersion over up to thirty-two channels using superposed fiber Bragg gratings[16,17]. This approach allows adjusting individually the dispersion level over each channel, rendering possible the compensation of the dispersion slope as well. Gires-Tournois interferometers are also suitable as multi-channel dispersion compensators, since their spectral response is naturally periodic with regards to the optical frequency. The Gires-Tournois interferometer is a Fabry-Perot interferometer with a totally reflective back mirror that was devised from the start as a dispersion compensator[18]. Except for intra-cavity losses, the Gires-Tournois interferomet r totally reflects light at all wavelengths. However, it

modulates the phase of the reflected light periodically with the optical frequency. As a result, the group delay is modulated periodically as well, photons at resonant (anti-resonant) optical frequencies making the most (least) round trips inside the cavity. The same group delay curve, and hence dispersion, can be applied over the spectral bandwidth of each channel when the spectral period of the interferometer, known as the free spectral range (FSR), equals the channel frequency spacing.

The Gires-Tournois interferometer was first used to compress laser pulses or compensate for the dispersion inside ultra-short pulse lasers[19-23]. Numerical simulations showed that dispersion compensation with such an interferometer could double the transmission distance of 8 Gb/s signals over an optical fiber link[24,25]. These simulations were followed by experiments that led to improvements in the transmission of optical signals at rates of 5 and 8 Gb/s[26,27]. Following this, Dilwali and Soundra Pandian evaluated theoretically the optical fiber ring resonator for dispersion compensation[28]. This resonator behaves similarly as the Gires-Tournois interferometer but operates in transmission rather than in reflection. Finally, Ouellette et al. compared the Gires-Tournois interferometer to the chirped fiber Bragg grating for dispersion compensation[29]. Their analysis underlined the limited capacity of the interferometer to provide a sizeable and constant dispersion over a large signal bandwidth.

The dispersion that can be achieved over a given bandwidth can be increased by cascading interferometers or by using multi-cavity interferometers[30-33]. This observation renewed the interest in the Gires-Tournois interferometer for dispersion compensation. A cascade of interferometers or a multi-cavity interferometer preserves the spectral periodic behaviour of each individual cavity as long as all cavities have the same FSR. They thus remain suitable for a multi-channel operation, while providing a level of dispersion that scales roughly as the number of cavities involved[31,33]. Design parameters that can be adjusted to obtain a desired dispersion response are the number of cavities, the reflectivity of the mirrors (other than the totally reflective back mirrors),

and the optical phase angle associated with a round trip inside each cavity. The design of a cascade of single-cavity interferometers is rather straightforward, the overall dispersion then being simply the sum of the dispersion of each individual interferometer[34]. The design of a multi-cavity interferometer is more involved because all cavities must be considered as a whole. It can rely on digital filter design techniques[30,31,35,36].

Dispersion compensation by a cascade of interferometers has been demonstrated using ring cavities [3,32-34,37-39] and micro-electromechanical (MEMS) Gires-Tournois interferometers[3,34,40,41]. Ring cavities present important limitations. Increasing the FSR requires a concomitant decrease in the ring radius. For example, a 50 GHz FSR requires a ring radius smaller than 1 mm. Small ring radii can result in intra-cavity optical losses[38]. The birefringence of small radius rings also produces a strong polarisation mode dispersion (PMD), that must be avoided by using light polarised along a principal axis of the rings.

Dispersion compensation by multi-cavity interferometers has been demonstrated experimentally as well. Jablonski et al. have developed thin-film-based two-cavity Gires-Tournois interferometers to compensate for the dispersion slope in very high bit rate optical time-domain multiplexing (OTDM) systems[42-47]. The thinness of their cavities translated into very large FSRs (many THz). Bulk multi-cavity interferometers made of a stack of thin-film-coated silica substrates have also been used for dispersion compensation[4,5]. The substrate thickness was adjusted to produce FSRs that matched current and future system channel spacings (50, 100 and 200 GHz).

A highly desirable feature for a dispersion compensator is tunability. The dispersion of a cascade of interferometers can be adjusted by varying the front mirror reflectivity of each interferometer as well as the optical phase angle associated with a roundtrip inside each said interferometer. Both parameters could be adjusted within the MEMS interferometers used by Madsen et al.[40,41]. Each interferometer comprised a silicon substrate supporting a thin membrane whose position was controlled with an electrical voltage. The combination of this membrane and the top surface of the silicon substrate acted, through a Fabry-

Perot effect, as a mirror with a reflectivity that could be adjusted electrically from 0 to 70%. The interferometer was completed by a highly reflective coating deposited on the bottom surface of the silicon substrate. The thickness of the substrate translated into a FSR of 100 GHz. The optical phase angle of the cavity was adjusted thermo-optically with a thermoelectric element controlling the temperature of the substrate. With a cascade of two such interferometers, the dispersion over a useful bandwidth of 50 GHz could be adjusted from -102 to +109 ps/nm. Two approaches have been used to adjust the dispersion of a cascade of ring cavities. In both cases, the optical phase around each cavity was adjusted thermally. Horst et al. used couplers that could be adjusted thermally as well [38]. Madsen et al. replaced each coupler by a Mach-Zehnder interferometer[3,34,37,39]. The coupling to each cavity was then varied by changing the temperature of one arm of the interferometer associated to it. The dispersion of a cascade of four such ring cavities could be varied from –1980 to +1960 ps/nm over a passband of 13.8 GHz corresponding to 60% of the FSR (23 GHz) of the device.

Jablonski et al. have used a variety of methods to adjust the dispersion of their multi-cavity device. Dispersion tunability was afforded, for example, by a variable thickness air gap [43,47] or by profiled thin film layers[44,45]. Dispersion was also varied by changing the number of reflections undergone by an optical signal zigzagging between two dispersion compensators[46].

The principle of operation of the dispersion compensator presented by Moss et al. ensures tunability[4,5]. Their compensator comprises two multi-cavity interferometers, each interferometer providing a dispersion that varies linearly over a given bandwidth. The dispersion slopes of the interferometers are equal in magnitude but of opposite signs. The dispersion resulting from cascading the two interferometers is proportional to the spectral shift between them, which is controlled thermally. This approach also applies when dispersion slopes are in a simple ratio. For example, a type A interferometer can be cascaded with two type B interferometers given that the dispersion slope of the latter is twice as small in magnitude.

A Gires-Tournois interferometer has a periodic spectral response and thus provides the same dispersion over all channels separated in frequency by the FSR of said interferometer. The interferometer does not provide compensation for the dispersion slope per se. Slope compensation has been built into the dispersion response of an interferometer as follows. Madsen et al. replaced the coupler to a ring cavity by an asymmetric Mach-Zehnder interferometer with arms of different lengths[37]. The asymmetric interferometer provides a coupling that varies slowly with wavelength. As a result, the ring cavity produces a dispersion that varies slowly from channel to channel. A similar behaviour has been obtained by Moss et al. through the use of a vernier effect[4,5]. As aforementioned, the dispersion in their compensator results from a spectral shift between two interferometers with linearly varying dispersions of opposite slopes. To obtain dispersion slope compensation, two interferometers with slightly different FSRs are used. The slight mismatch in FSRs produces a gradual shift between successive periods of the spectral response of the first interferometer with regards to corresponding periods of the second interferometer. This gradual shift translates into a dispersion level changing from channel to channel.

A number of patents are related to the compensation of dispersion with Gires-Tournois interferometers. Some are concerned with the tuneable compensation of dispersion within ultra-short pulse lasers[48-50]. Patents [51-53] disclose thin film structures that can be regarded as multi-cavity interferometers, developed also for laser applications. These inventions do not provide dispersion levels compatible with telecommunications applications. Patent [54] addresses the compensation of dispersion in an optical communication link with a Gires-Tournois interferometer. The cavity length of the interferometer could be adjusted to optimise the dispersion compensation. Patent [55] discloses the use of a cascade of interferometers or of multi-cavity interferometers for the compensation of dispersion. Configurations operating in transmission (ring cavities) and reflection (Gires-Tournois interferometers) are both disclosed. Jablonski et al. have deposited two patent applications disclosing their dispersion compensator[56,57]. A variety of geometries are presented to achieve multiple reflections on two thin-

film based multi-cavity Gires-Tournois interferometers facing one another. The tuneable dispersion compensator presented in [4,5] has been disclosed also in patent application [58]. The invention disclosed therein includes polarisation optics to shift laterally an optical beam, in order to achieve multiple reflections at a normal incidence on each multi-cavity Gires-Tournois bulk interferometers and hence increase the achievable dispersion levels.

A fiber Bragg grating consists in a quasi-periodic modulation of the index of refraction along the core of an optical fiber[59,60]. It is created by exposing a photosensitive fiber to a properly shaped intensity pattern of ultraviolet light. This light produces a permanent change in the index of refraction in selected sections of the optical fiber. The resulting optical fiber grating behaves as a wavelength-selective reflector having a characteristic reflectance spectral response. More or less complex spectral responses can be obtained by properly tailoring the refractive index modulation along the optical fiber. Their stability and reliability, in conjunction with their all-guided-wave nature, have made fiber Bragg gratings ideal candidates for fiber optic system applications. They are now used extensively in the field of optical telecommunications, e.g. for wavelength division multiplexing (WDM), for compensating chromatic dispersion in optical fibers, for stabilising and flattening the gain of optical amplifiers and for stabilising the frequency of semiconductor lasers.

The first fiber Bragg grating Fabry-Perot interferometer was realised in 1992[61]. It was made of two narrow band (0.3 nm) gratings with a constant period. The gratings were separated by 10 cm, leading to a 1 GHz FSR. Following this, wide band (150 nm) interferometers were demonstrated using chirped fiber Bragg gratings[62]. A low finesse interferometer with a FSR approaching 200 GHz was demonstrated with partially overlapping gratings. More recently, an interferometer with a FSR of 100 GHz and a finesse of up to 16 was obtained similarly with overlapping chirped fiber Bragg gratings[63]. The realisation of a wide band fiber interferometer with a FSR on the order of 50-200 GHz requires some overlapping of the chirped gratings found therein, because said gratings are longer than the required cavity length (0.5-2 mm). The successful operation of

these interferometers relies on the fact that interference between overlapping Bragg gratings is minimal. This fact was demonstrated more forcefully in references [16,17], where up to 16 gratings were superposed in a dispersion compensator, each grating compensating for the dispersion over a single channel as expected. Fiber Bragg grating interferometers have not been used for dispersion compensation. Moreover, it has not been generally recognised that wide band interferometers with FSRs of interest (50-200 GHz) can be produced using overlapping Bragg gratings. For example, it is stated in patent application [58] that : "Cavities are formed in the optical fiber between fiber Bragg grating reflectors. However a multi-cavity filter in fiber has a limited free spectral range (FSR) insufficient for a telecommunications system. For a typical 100 GHz FSR required in the telecommunications industry, the cavity length is about 1 mm. A Bragg grating reflector, if manufactured using commonly available grating-writing techniques, would need to be longer than 1 mm, and hence the two reflector cavity structure would be too long to achieve the necessary FSR."

SUMMARY OF THE INVENTION

The present invention relies on the use of Gires-Tournois interferometers for chromatic dispersion compensation. The interferometers are designed to produce a chromatic dispersion opposite that of an optical fiber link carrying an optical signal. More specifically, the disclosed interferometers are made of fiber Bragg gratings. A fiber Bragg grating consists in a quasi-periodic modulation of the index of refraction along the core of an optical fiber. Fiber Bragg gratings are now used extensively in the field of optical telecommunications, e.g. for wavelength division multiplexing (WDM), for compensating chromatic dispersion in optical fibers, for stabilising and flattening the gain of optical amplifiers, for stabilising the frequency of semiconductor lasers, and more generally in various filters. In the present instance, the fiber Bragg gratings act as the reflectors of all-fiber Gires-Tournois interferometers.

In accordance with one aspect of the present invention, the interferometers are made of chirped gratings with a wide band reflectivity response. Overlapping

gratings allows producing cavities short enough to obtain FSRs (50-200 GHz) that match the channel spacing of current and future optical communications systems.

Fiber Bragg grating interferometers can be used in a variety of ways to achieve dispersion compensation, as exemplified in embodiments described below. Gratings can be written with appropriately polarised UV beams in order to minimise birefringence effects[63]. Fiber Bragg grating interferometers thus avoid detrimental birefringence effects associated with small ring cavities, the latter being usable only with polarised light. The possibility of writing many overlapping gratings provides more flexibility for the design and fabrication of multi-cavity interferometers with desired dispersion properties. Their all fiber construction also ensures compactness and an increased stability and robustness in comparison to bulk interferometers.

Other advantages will become clear during the description of preferred embodiments with reference to the appended drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a single-cavity fiber Bragg grating Gires-Tournois interferometer according to a preferred embodiment of the invention.

FIG. 2 shows a multi-cavity fiber Bragg grating Gires-Tournois interferometer according to another embodiment.

FIG. 3 is a graph of the spectral variation of the group delay of a single-cavity Gires-Tournois interferometer.

FIG. 4 is a graph of the linear group delay of an ideal dispersion compensator.

FIG. 5 shows a cascade of two single-cavity Gires-Tournois interferometers according to yet another embodiment of the invention.

FIG. 6 shows a dispersion compensator with a multi-cavity Gires-Tournois interferometer.

FIG. 7 shows a tuneable dispersion compensator with multi-cavity Gires-Tournois interferometers.

FIG. 8 illustrates the principle of operation of a tuneable dispersion compensator based on a pair of multi-cavity Gires-Tournois interferometers.

FIG. 9 illustrates the operation of a tuneable dispersion compensator with a dispersion adjustment range centred around a non-zero dispersion.

FIG. 10 is a graph of a dispersion slope compensation with a vernier effect.

DESCRIPTION OF PREFERRED EMBODIMENTS OF THE INVENTION

A single-cavity fiber Bragg grating Gires-Tournois interferometer 30 in accordance with a first preferred embodiment of the present invention is illustrated in FIG. 1. Two Bragg gratings 13 and 14 are written in the core 12 of an optical fiber 10. The index modulations 13 and 14 can also extend inside the cladding 11 of the optical fiber 10 to avoid cladding mode losses. (The lateral extent of the index modulations 13 and 14 is limited by the lateral extent of the photosensitivity area of the optical fiber 10). Gratings 13 and 14 are identically chirped as illustrated by the varying period of the index modulations. The gratings are relatively shifted by a distance L along the fiber core 12, said distance determining the Gires-Tournois cavity length. The FSR of the interferometer is determined by the distance L and the group velocity of the fundamental mode of the optical fiber 10. Typically, a cavity length L of about 1 mm will lead to a FSR of about 100 GHz. The index modulation of grating 13, illustrated by thick lines, is strong enough to produce a reflectivity approaching 100%. The index modulation of grating 14, illustrated by thin lines, is weaker and produces only a partial reflectivity. Light propagating in the fiber core from side A is essentially totally reflected by the gratings, but undergoes a group delay that varies periodically with the optical frequency.

It should be noted that the gratings forming the interferometer creates some dispersion since the position of the two points at which light is reflected depends on the wavelength. In other words, the grating-based interferometer behaves somewhat as an ensemble of interferometers made of narrow band reflectors that are longitudinally shifted with regards to one another. However, this dispersion will be quite small with regards to dispersion levels that need to be compensated for in

practical applications. Moreover, it can be taken into account when designing a dispersion compensator based on fiber Bragg grating interferometers.

A multi-cavity Bragg grating Gires-Tournois interferometer 50 is illustrated in FIG. 2. It is similar to the single-cavity interferometer illustrated in FIG. 1, except that a third grating 15 has been added. Grating 15 is identically chirped to gratings 13 and 14. The longitudinal shift between gratings 14 and 15 is the same as the longitudinal shift between gratings 13 and 14, so that the length of the cavity defined by gratings 14 and 15 is the same as the length of the cavity defined by gratings 13 and 14. This ensures that the multi-cavity interferometer 50 still has a periodical spectral response with the same FSR as determined by distance L. The index modulation of grating 15, illustrated by dotted lines, produces a partial reflectivity. As with the single-cavity interferometer, light propagating in the fiber core from side A is totally reflected by the gratings, but undergoes a group delay that varies periodically with the optical frequency. The periodical variation of the group delay is however different from that obtained with the single-cavity interferometer. It depends on the reflectivity of each grating and on the optical phase associated with a round trip inside each of the cavities defined by gratings 13 and 14 and gratings 14 and 15. The interferometer illustrated in FIG. 2 has three reflectors and two cavities and thus represents the simplest form of a multi-cavity interferometer. It is understood that more gratings can be added in order to increase the number of cavities inside the interferometer.

FIG. 3 illustrates the periodical variation of the group delay with respect to the optical frequency of a single-cavity Gires-Tournois interferometer. The variation of the group delay over a spectral period is highly non-linear. This limits drastically the dispersion levels that are achievable with a single-cavity Gires-Tournois interferometer over a given bandwidth. An ideal dispersion compensator would rather produce a linear group delay as illustrated in FIG. 4.

Cascade of single-cavity interferometers

A linear group delay response can be approximated by cascading single-cavity Gires-Tournois interferometers, as shown for example in reference [34] with

interferometers not based on Bragg gratings. A practical implementation of this approach with fiber Bragg grating interferometers is illustrated in FIG. 5. A four-port circulator 40 has an input port 41, an output port 42 and two intermediate ports 43 and 44. Two single-cavity Gires-Tournois interferometers 30a and 30b with the same FSR are located in said intermediate ports. Light enters the circulator 40 by input port 41, is then successively reflected by interferometers 30a and 30b and exits said circulator by output port 42. It is understood that using an N-port circulator instead allows cascading N-2 interferometers. Other suitable means, such as a series of couplers, can be used to cascade interferometers as well. The temperature of each interferometer is preferably controlled with appropriate means, such as a thermoelectric cooler, in order to thermo-optically shift the spectral response of each interferometer. The mostly linear group delay response is obtained by properly positioning the spectral responses of the interferometers with regards to one another.

One advantage of chirped Bragg gratings is the easiness in controlling their reflectivity. By varying the strength of the index modulation along the fiber, it is very simple to produce such gratings with a reflectivity that depends on wavelength in a predetermined fashion. A cascade of interferometers made of fiber Bragg gratings with spectrally dependent reflectivities can be fabricated. Such a cascade will produce a dispersion that varies from channel to channel, thus allowing the compensation of the dispersion slope as well.

Multi-cavity interferometer

The dispersion achievable over a given bandwidth can also be increased by using a multi-cavity Gires-Tournois interferometer and a three-port circulator, as illustrated in FIG. 6. Light enters the circulator 40 via input port 41, is then reflected by multi-cavity Gires-Tournois interferometer 50 located in intermediate port 43 and then leaves the circulator via output port 42. Means other than a circulator, such as a coupler for example, can be used to extract the light reflected by the interferometer. The temperature of the multi-cavity interferometer is controlled by appropriate means, such as a thermoelectric cooler, in order to align the periods of

its spectral response with transmission channels. The multi-cavity int rferometer is designed to produce a group delay response approximating the linear response illustrated in FIG. 4. The design parameters to this end are the number of cavities, equal to the number of gratings other than the highly reflective one, the reflectivity of the gratings other than the highly reflective one, and the relative optical phase associated with a roundtrip inside the cavities defined by neighbouring gratings. The possibility of writing many overlapping gratings, demonstrated for example in reference [16,17], provides more flexibility in approximating a linear group delay over a sizeable fraction of each period of the spectral response of the interferometer. During fabrication, two physical parameters can be used to control the relative optical phase of the cavities, i.e. the distance between the gratings and the average refractive index distribution along the fiber. The distance between the gratings can be controlled by writing them successively and changing between each the relative position of the optical fiber and the phase mask used to write said gratings with a sub-wavelength accuracy motion stage. The gratings can also be written simultaneously using a complex phase mask that predefines their relative positions. Once the gratings have been written, UV-exposure can be used to slightly modify the index of refraction of the fiber, a technique known as UV-trimming. Changing the refractive index of the optical fiber changes the optical phase of light propagating through it. Equivalent techniques to control the relative optical phases of the cavities of a multi-cavity interferometer are not available for the fabrication of bulk interferometers.

Pair of multi-cavity interferometers

A tuneable dispersion compensator can be fabricated using a pair of multi-cavity interferometers as disclosed in the prior art patent application [58]. A fiber Bragg grating implementation of this approach is illustrated in FIG. 7. The set-up is the same as for a cascade of two single-cavity interferometers illustrated in FIG. 5, except that the single-cavity interferometers 30a and 30b have been replaced by multi-cavity interferometers 50a and 50b. Multi-cavity interferometers 50a and 50b have the same FSR. They produce over each period of their spectral response a

dispersion that varies lin arly, their dispersion slopes being equal in absolute value but of opposite signs. The temperature of both interferometers is controlled by appropriate means, such as thermoelectric coolers, in order to vary the spectral shift between the two.

The principle of operation of such a dispersion compensator is illustrated in FIG. 8. Graphs on the left represent the group delay of the interferometers while those on the right represent their dispersions. These graphs are representative of an ideal case where the group delay of each interferometer is parabolic over the whole period of the spectral response. Thin curves apply to individual interferometers 50a and 50b, whereas thick curves represent the sum of their group delays and dispersions available at output port 42. In the top graphs, the spectral responses of the interferometers are perfectly aligned. The sum of their group delays is then constant and a zero dispersion results. As the spectral shift between the interferometers increases, so does the slope of the resulting group delay and hence the dispersion. Inverting the spectral shift produces a negative dispersion rather than a positive one as shown in FIG. 8. This figure also shows that an increase in dispersion comes along with a concomitant decrease in the useful bandwidth over which the desired dispersion is obtained. (The zones of negative dispersion in FIG. 8 are undesirable artefacts resulting form the superposition of neighbouring periods of the spectral responses of the interferometers.)

The group delay represented by the dotted curves in FIG. 8 is quite reminiscent of the group delay of a single-cavity Gires-Tournois interferometer shown in FIG. 3. As disclosed in patent application [58], a three-cavity Gires-Tournois interferometer suffices to transform the natural group delay curve of a single-cavity Gires-Tournois interferometer into a positive parabola covering most of the period of the spectral response. On the other hand, a group delay curve that has the shape of a negative parabola, as illustrated by the thin solid curves in the left graphs of FIG. 8, is more difficult to obtain over a sizeable fraction of the spectral response period, given its greater dissimilarity with the natural Gires-

Tournois behaviour. The possibility of superposing many fiber Bragg gratings gives more flexibility in achieving this objective.

The use of Bragg grating-based interferometers alleviates some of the drawbacks of prior art devices. For example, a bulk multi-cavity interferometer is more easily manufactured when the optical path length of each cavity is the same. The fabrication can then proceed as follows. A substrate of a suitable optical material is first polished to a thickness providing the desired FSR. It is then cut into pieces that are thin-film coated and assembled to form the multi-cavity interferometer. The equality in optical thickness for all cavities results in the group delay curve of the multi-cavity interferometer being symmetric over each period of the spectral response. This is the case for the multi-cavity interferometer disclosed in patent application [58]. This symmetry has an unfortunate consequence: a pair of interferometers with symmetric group delay curves produces a dispersion adjustment range that is centred around a zero dispersion level, as illustrated in FIG. 8. All results obtained with this type of dispersion compensator that have been published to this day are consistent with this observation[4,5]. In order to centre the dispersion adjustment range around a non-zero dispersion, it is necessary to introduce some asymmetry in the spectral response of one interferometer. This case is illustrated in FIG. 9, where the group delay represented by thin solid curves in the left graphs is clearly not symmetric over a period of the spectral response. As seen in the top graphs, the dispersion takes a non-vanishing value when the spectral responses of the interferometers are perfectly aligned. A thermally-induced spectral shift between the interferometers results in a variation of the dispersion around this non-vanishing value. Producing a bulk multi-cavity interferometer with an asymmetric group delay curve, and thus with a different optical phase from cavity to cavity, will be much more difficult to fabricate. Fiber Bragg grating fabrication techniques are better suited for this task.

Also in the prior art, the vernier effect has been used to implement some dispersion slope compensation with a pair of multi-cavity interferometers of slightly different FSRs[4,5]. This approach is illustrated in FIG. 10, where the group delay curves have slightly different periodicities. The first periods to the left of the graphs

are perfectly aligned, so that dispersion over this channel vanishes. The increasing shift between the periods resulting from the difference in FSRs produces a dispersion that increases from channel to channel when moving to the right of the graphs. Shifting further the spectral response of one interferometer with regards to the other, by thermal means for example, adds the same dispersion to all channels without modifying the dispersion slope created by the difference in FSR, as illustrated in the middle and lower graphs in FIG. 10. This approach has two disadvantages. Firstly, the dispersion slope is not proportional to the absolute dispersion level but remains constant as determined by the difference in FSRs of the two interferometers. This behaviour does not match the evolution of the dispersion affecting an optical signal propagating along an optical fiber. The dispersion in each channel increases proportionally to the distance of propagation in the fiber, albeit at a possibly different rate from channel to channel. Under such conditions, it is clear that the difference in dispersion between two channels will be proportional to the dispersion level in each. Secondly, dispersion slope compensation through a vernier effect uses up some of the dispersion adjustment range afforded by the multi-cavity interferometers, as seen in FIG. 10. This is so because the dispersion slope compensation and the thermally induced dispersion both result from a relative shift between periods of the spectral response of the interferometers, the allowed total shift being limited by the minimum fractional bandwidth of each channel over which the dispersion compensation is required.

The vernier approach can be implemented with fiber Bragg grating interferometers. However, when compared with prior art devices, fiber Bragg gratings offer a much better approach towards dispersion slope compensation. One can use a pair of multi-cavity interferometers made of fiber Bragg gratings, each grating (other than those with a high reflectivity) having a reflectivity that varies with the optical frequency. The spectral variation of the reflectivity of the gratings is designed in such a way that each interferometer still produces a dispersion that varies linearly over a sizeable fraction of each period of its spectral response. However, the slope of the linearly varying dispersion of each interferometer varies from channel to channel. The dispersion of the pair of

interferometers will thus vary linearly with the th rmally induced sp ctral shift between them, as previously, but at a rate that will vary from channel to channel. This method will provide a dispersion slope compensation that is proportional to the dispersion levels in each channel. A properly designed pair of interferometers will actually be capable of compensating for all orders of dispersion. Moreover, the useful fractional bandwidth over which the dispersion compensation is achieved will be the same for all channels.

In conclusion, fiber Bragg grating Gires-Tournois interferometers can be used for dispersion compensation. These interferometers avoid the birefringence limitations of ring cavities. They are compact and will likely be more robust than their bulk counterparts. Fiber Bragg grating fabrication techniques will make it easier to control the relative optical phases of cavities in multi-cavity interferometers. The spectral variation of the reflectivity of fiber Bragg gratings can also be controlled easily. This will allow the design and fabrication of devices capable of compensating for all orders of dispersion.

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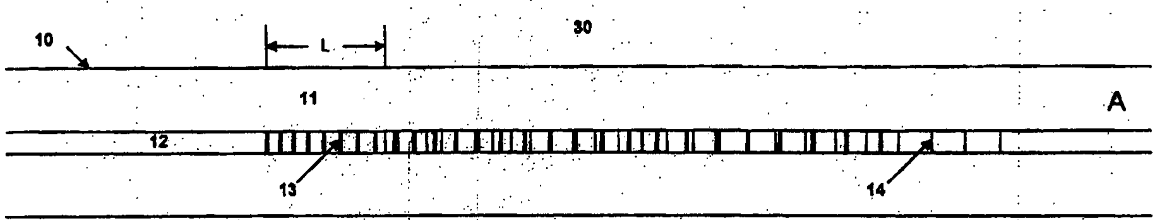

FIG .1: Single-cavity fiber Bragg grating Gires-Tournois interferometer.

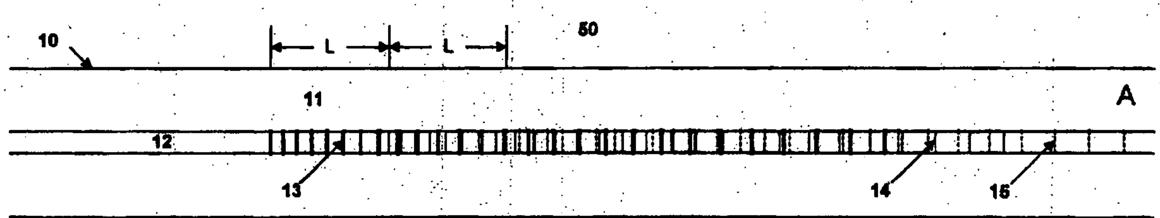

FIG. 2: Multi-cavity fiber Bragg Gires-Tournois interferometer.

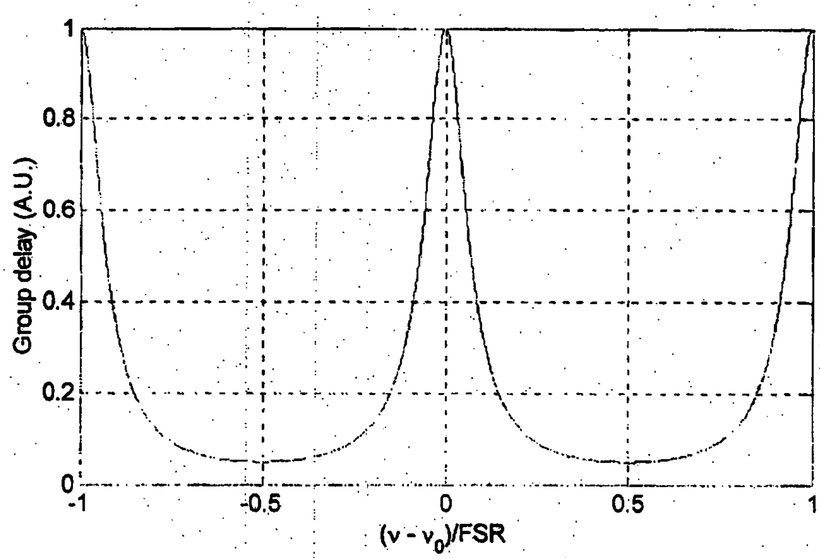

FIG. 3: Spectral variation of the group delay of a single-cavity Gires-Tournois interferometer.

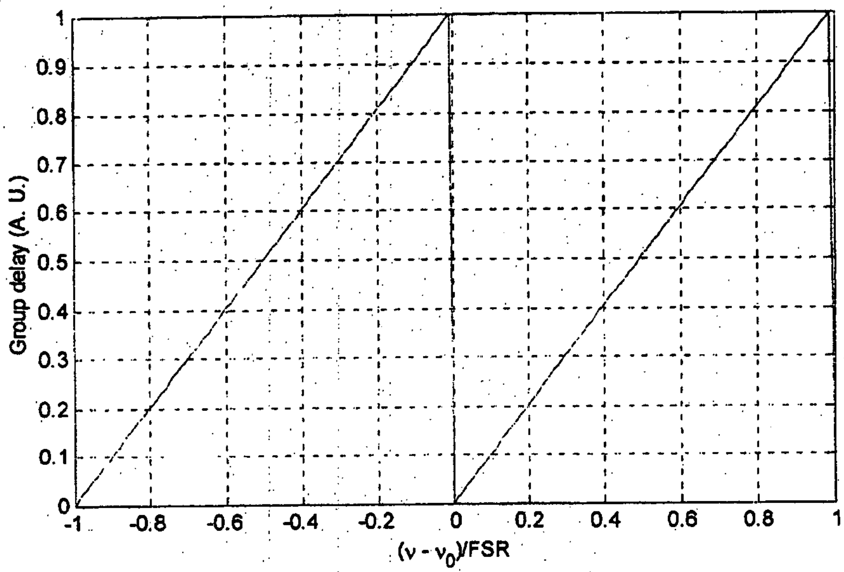

FIG. 4: Linear group delay.

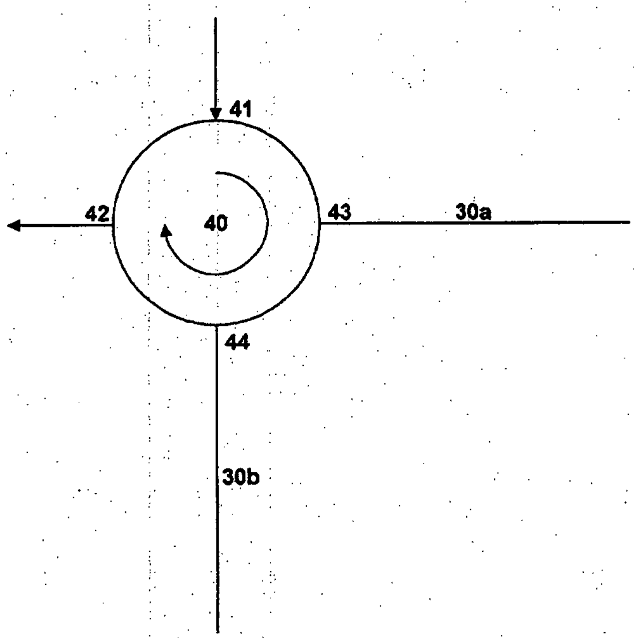

FIG. 5: Cascade of two single-cavity Gires-Tournois interferometers .

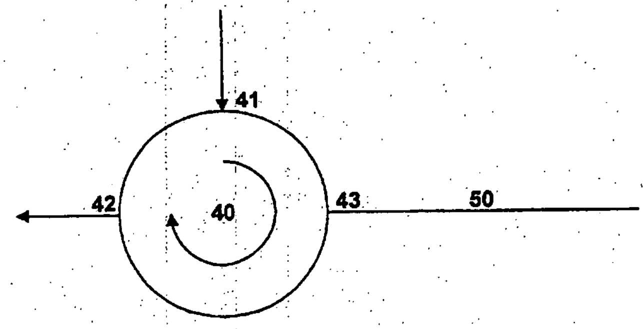

FIG. 6: Dispersion compensator with a multi-cavity Gires-Tournois interferometer.

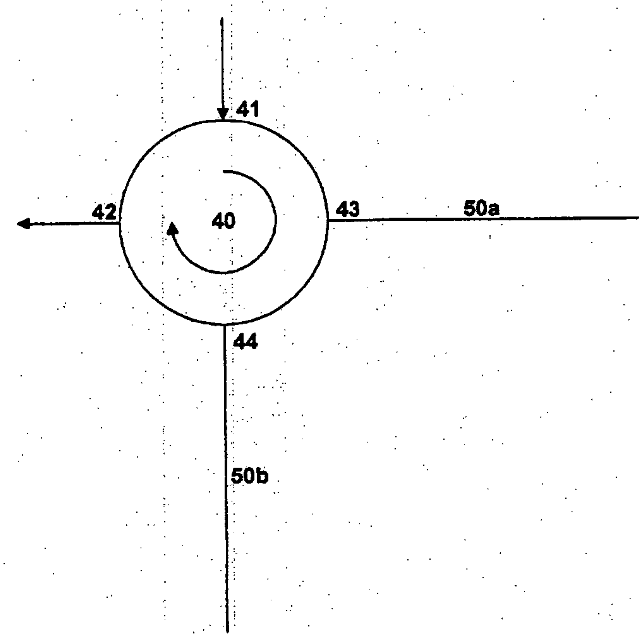

FIG. 7: Tunable dispersion compensator with multi-cavity Gires-Tournois interferometers.

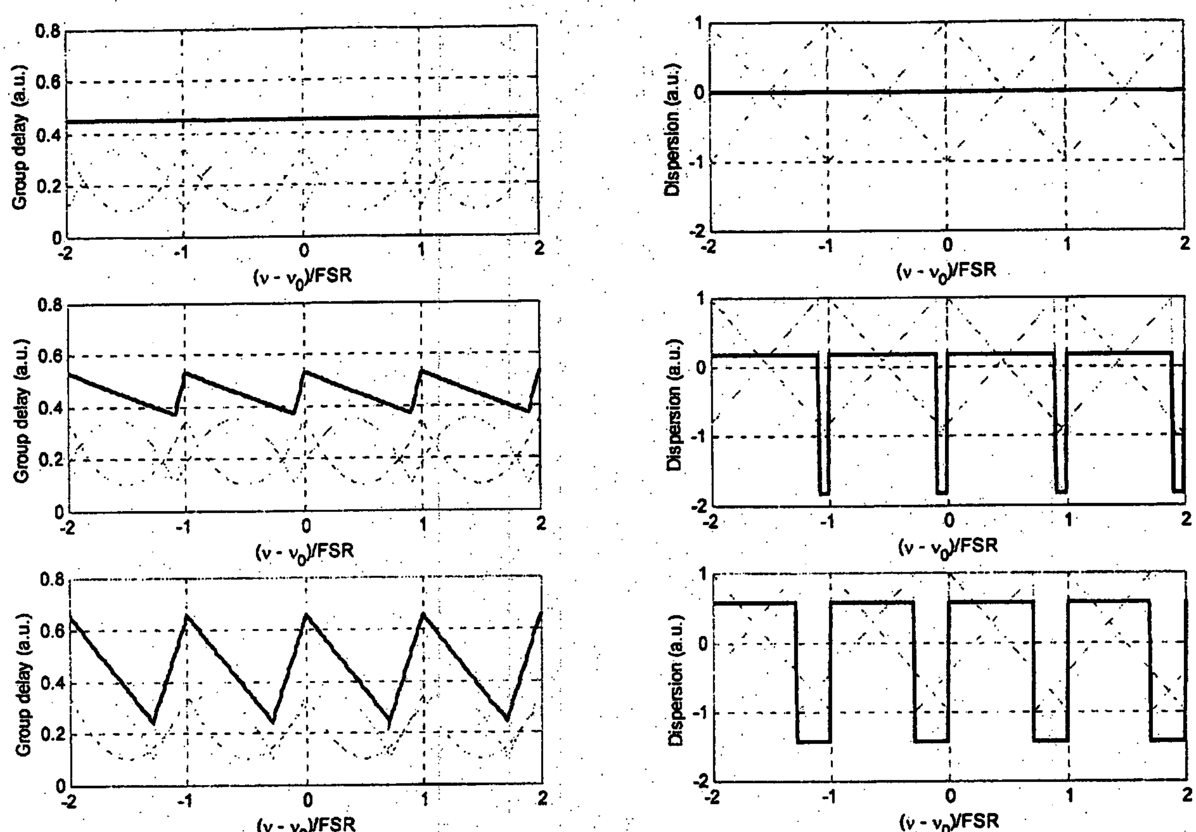

FIG. 8: Principle of operation of a tunable dispersion compensator based on a pair of multi-cavity Gires-Tournois interferometers.

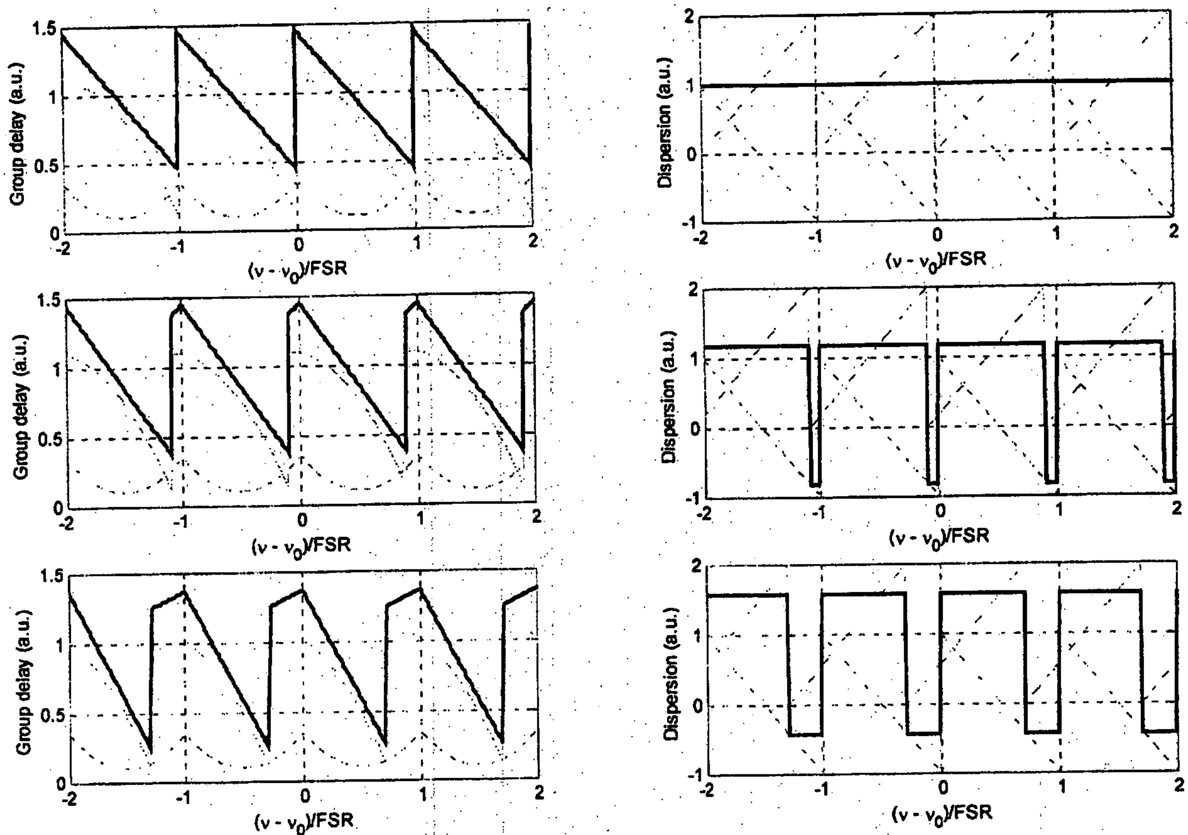

FIG. 9: Operation of a tunable dispersion compensator with a dispersion adjustment range centered around a non-zero dispersion.

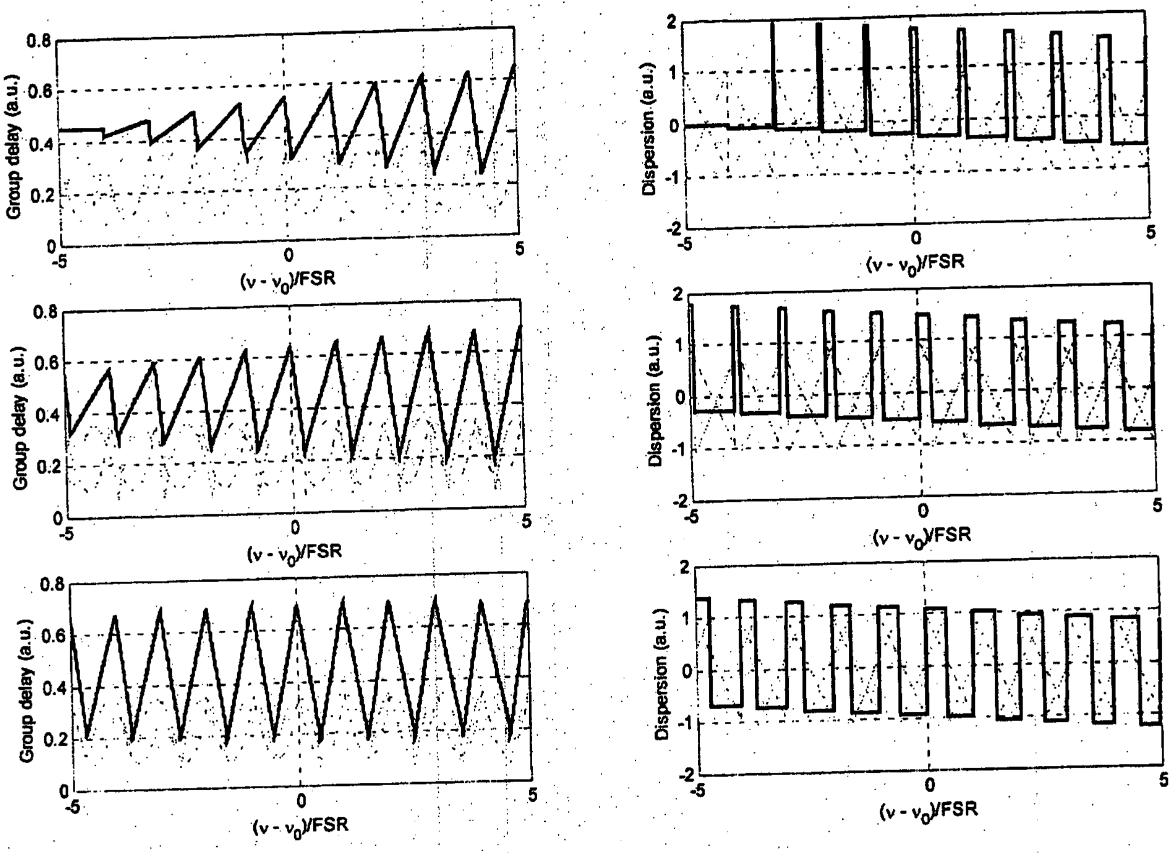

FIG. 10: Dispersion slope compensation with a vernier effect.